Experimental abrasion of water submerged bone: the influence of bombardment by different sediment classes on microabrasion rate.

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Abstract

Data presented here demonstrates the utility of quantitative analysis of sediment-induced microabrasion on bone's surface. Fresh sheep (*Ovis aries*) bone, acting as a human analogue, was bombarded by mobile sediments from silt, sand and gravel classes (ranging 20μm-3.35mm) in a series of flume-based experiments. Controlled bombardment produced unique abrasion patterns on bone which were recordable using scanning electron microscopy. Imaging abrasion at both x100 and x1000 magnifications allowed quantitative and qualitative distinction to be made concerning the sediment class that the bone was abraded by; bombardment by gravel classes caused abrasion to advance through cyclical cracking, whereas smoothing of bone's surface occurred more frequently in sand and silt classes. A stepwise multi-linear regression model identified changes in sediment grain size ($p<0.001$), duration of exposure to abrasion ($p<0.001$), sphericity of the abrasive ($p=0.002$), and T value (abrasive force) ($p=0.013$) respectively, as the strongest rate limiting factors controlling microabrasion propagation. The methodology presented herein demonstrates analytical value by allowing diagnostic modifications to bone's surface to be correlated with specific taphonomic processes. Data developed from flume-based experimentation was applied in four separate case studies; abrasion data recorded on bones recovered from different aquatic contexts, was linked to hydrological and marine seabed sediment data to demonstrate how documented microabrasion can reflect the different sedimentary contexts bone has passed through. In light of these results we suggest that a quantitative approach to analysing abrasion on bone retrieved from water has potential to allow remains' submersion times and transport pathways to be established with a higher degree of resolution than is currently possible. The development of improved methodologies for the interpretation of submerged human bone is vital due to the increasing risks posed by flooding and coastal erosion to archaeological sites.

Keywords: Fluvial Taphonomy; Human Remains; Sediment Abrasion; Aquatic Environments; SEM.

1. Introduction

The development of improved methodologies for the interpretation of submerged human and other animal bone is of considerable importance as a variety of anthropogenic and natural-environmental pressures threaten archaeological sites located around water bodies (river systems, lakes and the coast). Taking the UK as an example, while the full extent of risk to sites holding skeletal remains is not known, there are in excess of 20,000 archaeological and historical sites located in coastal and intertidal areas (EH RCZAS, 2009). English Heritage has stated that climate change threatens the survival of thousands of sites through the effects of coastal erosion and flooding (Cassar, 2005). A lack of frequent quantitative monitoring of these resources and the often unpredictable nature of rapid, stochastic erosion events means destructive processes acting on these sites are not effectively mitigated (Chapman *et al*., 2002; Flatman, 2009). Consequently, associated skeletal material from at risk sites become exposed to and displaced into water.

Currently the interpretation of isolated, water-transported human remains presents a number of challenges to archaeologists. Bone entrained in a flow may be moved large distances from an original depositional context and be subject to a wide range of diagenetic alterations (physical, chemical and biological processes) that hinder osteological analysis (Haglund and Sorg, 2002; Mays, 2008; Sorg *et al.,* 1997). Within the discipline of archaeology there is a need for methods which facilitate accurate interpretations of remains' submersion times, transport pathways and provenances. Such methods would also have useful applications in the fields of palaeontology and forensic taphonomy. Currently, analysis of taphonomic pathways from aquatic environments is often limited to a qualitative assessment of skeletal completeness and gross morphological change on the bone. One such modification that is frequently observed on submerged bone is abrasion, caused by impacting mobile sediments entrained in a flow (Cook, 1995; Haglund and Sorg, 2002; Littleton, 2000). Therefore, to better understand the taphonomic histories of skeletal material recovered from water an ideal solution would be the development of numerical models for the abrasion rates of bone, which are easily relatable to different flow velocities, the nature of the impacting sediment and the structural properties of bone itself.

Previous studies have attempted to correlate extents of abrasion on bone surfaces with pertinent taphonomic information, such as duration of bombardment, transport distances, and exposure to different sediment classes (Cook, 1995; Nawrocki *et al.,* 1997). However, determining the exact origin of abrasive modifications on submerged bone by accurately correlating degrees of abrasion with specific taphonomic processes and durations has proven difficult at a gross morphological scale; as abrasive changes progress slowly (Shipman and Rose, 1988) and are hard to differentiate and assign temporal specificity (Cook, 1995). As a result there is a limited understanding of whether such physical modifications can be used to accurately establish remains' spatio-temporal parameters of submersion, and whether this lack of elucidation is due to the complexity of hydrodynamic processes modifying bone or the resolution of analyses used to interpret modifications.

A recent study by Thompson *et al,* (2011) shows preliminary success in quantitatively relating bombardment by mobile sediments to microabrasion propagation on submerged bone. However, to achieve a better understanding of the hydrodynamic processes modifying bone, which may ultimately help to facilitate the successful reconciliation of taphonomic effect, cause and duration when analysing bones' aquatic taphonomic pathways, further experimental work is needed.

Therefore, using laboratory flume experiments and quantitative recording of abrasive/hydrodynamic processes, this study builds on the work of Thompson *et al.,* (2011) and aims to gain a more nuanced understanding of the influence that different sediment classes and morphologies have on the abrasion rate of bone at a microstructural level. In addition, this study aims to achieve a more in-depth understanding of the different mechanisms and variables influencing microabrasion rate, such as abrasive force and duration of exposure to bombardment.

1.1 Current analytical approaches

Aside from stable isotope analysis (for example see Meier-Augenstein and Fraser, 2008) current approaches for interpreting water transported remains have limited applications in the analysis of isolated, decontextualized skeletal tissue. In addition, while the isotopic composition of remains can generate useful data concerning the potential geographical origins of transported skeletal material (Meier-Augenstein and Fraser, 2008), such analysis does not provide direct information regarding the taphonomic histories of remains upon entering water. Therefore, any taphonomic information detailing transport pathways and durations may provide useful additional and supporting data when attempting to establish submerged remains' provenances and original depositional contexts.

Archaeological, paleontological and forensic studies concerning aquatic bone taphonomy have a number of commonalities in approach and cross-discipline applications. Archaeological and paleontological disciplines largely employ field-based observations of fluvially deposited human and faunal assemblages (see for example Aslan and Behrensmeyer, 1996; Behrensmeyer, 1982; Gifford and Behrensmeyer 1977; Stojanowski, 2002), and laboratory flume experiments to recreate transport and modification processes (for example Boaz and Behrensmeyer 1976; Coard, 1999; Peterson and Bigalkel, 2013; Trapani, 1998). Others have adopted a geochemical approach, using the trace element compositions of fossil bone from marine vertebrate assemblages to determine a degree of mixing and taphonomic averaging (see Trueman *et al.,* 2003).

In large, these studies relate the transport and hydrodynamic sorting potentials of different skeletal elements to variations in their size, density and shape. Such studies are principally concerned with establishing whether the composition of fluvially deposited assemblages have been biased by taphonomic agents; this is achieved by determining whether remains have been moved from a primary depositional context and are autochthonous (locally-derived) or allochthonous (non-local) in nature. Consequently, estimations of transport distance are only established relative to the frequency and distribution of remains in and between sites. Therefore, this approach relies on the analysis of multiple skeletal elements from defined stratigraphic contexts.

While hydrodynamic sorting methodology has proven to be a very useful approach for determining whether remains have been transported in water, the application of this methodology to the analysis of isolated bone, rather than skeletal assemblages, may lead to inaccurate or incomplete conclusions: Simply relating a distance transported to a degree of skeletal completeness is problematic, as the recovery of disarticulated skeletal elements, with high transport potentials, is not necessarily indicative of long distance transport. For example, during rapid erosion and re-deposition events, such as flooding, skeletal elements may enter water, become isolated; but only travel short distances before burial in bottom sediments. In addition, Coard & Dennell (1995) have shown that articulated elements generally have equal or greater transport potentials than those which are disarticulated. Furthermore, studies by Herrmann *et al.* (2004) and Nawrocki and Baker (2001) indicate that Fluvial Transport Indices (FTI) as defined by Boaz and Behrensmeyer (1976) and Voorhies (1969) are not always accurate predictors of remains' transport potentials in natural settings, due to variability in hydrodynamic systems and the physical constituents of bone itself.

Methods that qualitatively assess the degree of rounding or smoothing on bone to suggest a distance transported, or period of exposure to bombardment, are based on the principals of mobile sediment grain modification. As a general rule of sediment transportation, movement in a flow causes progressive rounding of grains, hence allowing connections to be made between hydrological conditions, particle morphology and duration of transport in relative terms. However, as Behrensmeyer (1975) has shown, variations in the size, density and shape of bone means the hydrodynamic properties of different skeletal elements are less homogeneous than those of sediment clasts; therefore different elements cannot be considered hydrodynamically equivalent (Hanson, 1980). Variability in the hydrodynamic properties of bones does allow distinctions to be made concerning the transport potentials of different remains entrained in a flow, but presents potential difficulties when attempting to accurately relate degrees of rounding/ smoothing across a range of bone classes to a transport distances or period of bombardment (Cook, 1995). Furthermore, these are qualitative measures of change that lack temporal specificity.

Forensic taphonomy studies have a more direct focus on the analysis of isolated skeletal tissues, with the aim of elucidating Post Mortem Submersion Intervals (PMSI) and transport histories. Therefore, this data has good potential cross-discipline applications in the analysis of isolated archaeological remains. However, correlations between disarticulation sequences of remains and PMSI have proven problematic in forensic contexts (Haglund, 1993) and also work under the principal of some degree of connective tissue being present upon deposition in water. In addition, while biological markers such as rasping and boring gastropods attached to bone have shown good potential application in approximating location and period of submersion, this is a relatively under explored area (Haglund and Sorg, 2002; Skinner *et al.,* 1988; Sorg *et al.,* 1997). Furthermore, biological markers may produce modification data that is only relevant within a defined geographical context; as local variability, such as biodiversity and seasonality, dictate the succession of different modifying agents which may limit the universal application of these observations. Consequently, when establishing PMSI and transport pathways of skeletonised remains in medico-legal contexts, analysis is often limited to qualitative assessment of gross morphological abrasion, measures of skeletal completeness (see for example; Nawrocki *et al.,* 1997) and estimations of remains transport potentials, which draw from the archaeological and palaeontological data. In addition, comparisons with diagentically-altered remains from case studies, whose spatio-temporal parameters of submersion are not always clearly defined, may also have to be utilised (Nawrocki *et al.,* 1997).

1.2 The potential of quantitative approaches

It is clear that macroscopic analysis of abrasion and observation of skeletal completeness, which may be used in current interpretations of water modified bone, do not fully account for the complexity of the aquatic taphonomic systems at work. Quantitative experimental methodology, as we present herein, offers an alternative approach to, and understanding of, this problem. Experimental approaches attempt to better understand past modifying processes by duplicating them empirically (Coles, 1979). For example, experimental reproductions of wear indices have been commonly employed to ascertain the function of bone tools (see for example Greenfield, (1999)) and to distinguish between use-wear and natural environmental modifications to bone (see for example Blackwell and d'Errico, (2008)). Taphonomic process studies are principally concerned with relating an effect to a cause, and establishing the predictability of such relationships to determine whether diagenetic changes can be correlated with specific taphonomic agents. Therefore, adopting a quantitative experimental approach facilitates a better fundamental understanding of modifying processes by allowing trends in bone tissue modification to be established with more certainty, hence limiting diagnostic ambiguity.

2. Material and Method

2.1. Bone samples

Sections of fresh adult sheep (*Ovis aries*) femora (c. 1 inch in length) were bombarded by mobile sediments in a series of flume based experiments. Due to difficulties with the availability of human archaeological bone in very similar digenetic states or pre-abrasion starting points, these fresh bone analogues were utilised to

Figure 1. Example of defleshed sheep bone used in bombardment experiments prior to sectioning.

ensure that the material being abraded was as structurally homogeneous as possible. Furthermore, archaeological material was not selected due to ethical considerations surrounding destructive analysis. Sheep bone's structural properties, and organic and inorganic compositions are very similar to those of modern human bone (Rehman *et al.,* 1995) and therefore are appropriate analogues as they react in comparable ways to stress and abrasive forces. Issues concerning the application of fresh bone analogues to the study of archaeological material are discussed in **Section (4.5.)**. Samples (**Figure 1**) were de-fleshed following an enzyme maceration method described by Simonsen *et al.* (2011), and classed at stage 0 on the Behrensmeyer (1978) weathering scale.

The possibility that trends in microabrasion propagation could be adversely influenced by potential variance in structural integrity between different bone specimens was considered. To control for this, sections of long bone from multiple specimens where bombarded by each sediment type.

2.2. Abrasion experiments

The full experimental design for flume based sediment bombardment of bone is given in Thompson *et al.* (2011). In brief, bone samples were placed in a fully calibrated laboratory annular flume and bombarded with a range of sediment classes and sizes (**Table 1**) over fixed time periods of 24, 48, 72 and 120 hours. Sediment sizes used were chosen based on the standard Wentworth scale (Wentworth, 1922), and were selected to provide a comprehensive range of grain sizes, which could be accommodated within the mini flume. The time periods chosen followed those utilised by Thompson *et al.,* (2011) as these have proven appropriate for understanding incremental changes to the surface of bone by allowing small scale changes (initial modifications) as well as extensive alterations to be documented. A control sample was also placed in the flume without any sediment load to observe the influence of fluid shear force acting on the bone alone.

Sediment class	Median grain size (d50)
Silt	38µm
Sand	152.5µm, 362.5µm, 512.5µm, 700µm, 925µm
Gravel	2mm, 3mm.

Table 1. Summary of sediment classes and sizes used in flume based bombardment experiments

The use of annular flumes as opposed to tumbler based experiments is important, as the latter cannot accurately model sediment transport processes within a benthic boundary layer, as found in natural settings (Cook, 1995; Kuenen, 1956; Thompson *et al.,* 2011). To minimise experimental durations, bone was abraded by saltating sediment particles, as Thompson *et al.* (2011) show that sediment transport

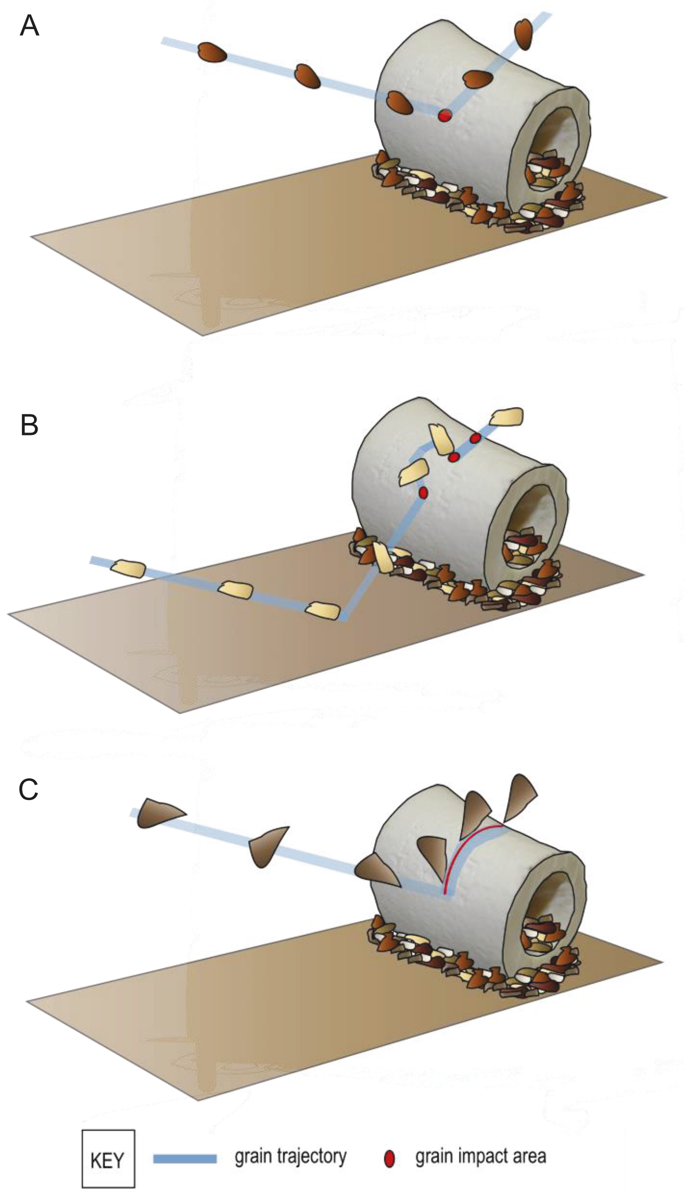


Figure 2. Variability in the way sediment impacts bone will influence its abrasive potential.

A. Direct 90 degree impacts by saltating grains causes the highest degree of abrasion though ablation.

B. An ascending grain may produce more numerous but less energetic impacts.

C. Variations in grain morphology may result in sediment losing momentum before impact and scraping the bone surface.

in this mode causes maximum abrasion to fresh bone. Samples were attached to the flume floor to simulate static/stationary bone; this limited the amount of potential variables, such as bone on bone impact and interaction with the flume walls, which could influence microabrasion propagation, and allowed maximum abrasion over fixed time periods to be recorded.

2.3. Calculations of abrasive force

To facilitate an energy-based assessment of abrasion, number of impacts per second, impact trajectory and velocity of saltating sediment grains were recorded using a Casio's Exilim Pro EX-F1 high speed video camera, recording at 1200 frames per second (fps). Data for silt particles could not be collected, as they were too small to accurately record. Figure 2 demonstrates how variability in the way sediment impacts bone, such as angle of impingement, will influence its abrasive potential. The relative abrasive forces (*T* Value) of different sediment sizes, measured in Pascals (Pa), were then calculated using the impact wear equation provided in (Amos *et al.*, 2000)

$$T = (NM_g[\sqrt{U_y^2 + W_s^2}\,]\,/\mathcal{E}A_r)\ Pa,$$

Where T is an expression of the ballistic momentum or abrasive force of the sediment, N is number of impacts per unit area per second; M_g is sediment grain mass, $\sqrt{U_y^2 + W_s^2}$ is speed of impact; and $\mathcal{E}A_r$ is an efficiency term dependant on the transfer of momentum from the grain to the bone ($\mathcal{E}$) and the area of impact (A_r). Impacts for all samples were measured over the same fixed area (c.1cm^2) on the upstream side of the bone where they were most frequent. This equation accounts for the elastic properties (Young's modulus) of the abrasive, and based on previous observations by Thompson *et al.* (2011) we assume that bone acts as a quasi-brittle material, experiencing deformation wear when bombarded. To allow for an assessment of the effect of sediment grain morphology on abrasion rate, grain sphericity and angularity were determined using the Krumbein roundness chart (Krumbein and Sloss, 1951). Sediments' physical and hydrodynamic properties are summarised in **Table 2**.

Median grain size	**152.5µm**	**362.5µm**	**512.5µm**	**700µm**	**925µm**	**2mm**	**3mm**
Median grain mass (g)	0.000002	0.000029	0.0002	0.0006	0.001	0.0024	0.0072
Mean impacts per second	3.37	3.71	21.85	9.11	18.62	1.76	1.05
Mean impacts velocity (cmps)	63.6	24.2	25.9	29.02	29.47	36.7	34.3
Mean impact trajectory (degrees)	87.2	90.9	92.03	87.55	87.56	87.34	93.22
(T) value, Pa	0.03	0.16	0.10	0.20	0.23	3441.77	5522.12
Grain sphericity	0,7	0,8.5	0,7	0,9	0,9	0,3	0,3
Grain angularity	0,4.5	0,7	0,5	0,7	0,7	0,7	0,5
Grain Reynolds number (Re)	5.40	14.74	25.93	37.25	54.06	143.02	292.94

Table 2: Summery of sediment's physical and hydrodynamic properties

2.4. Image analysis and abrasion score calculation.

Imaging and calculation of abrasion followed methods in Thompson *et al.* (2011). In total, 1152 pre and post abrasion scans of bone's surface were taken using a Hitachi TM1000 scanning electron microscope (SEM). For each bone sample nine regions of interest (ROIs) were selected (**Figure 3**). Each ROI was imaged at two magnifications (x100 and x1000). Using the public domain software ImageJ, ROI scans were gridded into concentric cells of which the central 15 were examined. Missing data was minimal, allowing c.540 total (pre and post) abrasion cells to be

Figure 3. Nine regions of interest (red areas) where imaged on impacted, upstream side of bone.

aligned and analysed for each bone sample/time interval. Four types of abrasion were recorded, which effectively encompass all types of observed surface change; ablation (surface area removal), cracking (the appearance of or increase in length or width of surface fissures; pitting (the appearance of or increase in diameter of non-linear, edge bounded features; and displacement (the lateral movement of material across the visible surface) (Figure 4). Ablation abrasion took two distinct forms; (a) material being removed through smoothing of the bone surfaces and (b) being broken off in individual pieces as a result of progressive cracking. The two occurrences of ablation where both simply treated as removal of surface material, as the differences in depth of abrasion caused by the two mechanisms were hard to determine using 2D imaging. An abrasion score of 0-9 for each abrasion type was assigned to post-abrasion cells. Scores assigned to cells were calculated based on the surface area each abrasion type affected. Where multiple abrasion types were present in each post-abrasion cell all types were recorded. Where cells could not be matched due to heavy abrasion (as was sometimes apparent for gravel induced abrasion) these areas received the highest ablation abrasion score. This approach facilitates a semi-quantitative interpretation of microabrasion propagation and allows abrasion to be represented as a common numerical expression, hence overcoming the subjectivity associated with more qualitative assessments of abrasion, such as measures of rounding or smoothing on bone's surface. Abrasion scores are represented as percentage values of change and material loss. Total percentage abrasion and percentage abrasion of each contributing abrasion type were calculated at both magnifications and as combined total values. The frequency of each contributing abrasion type was also calculated. Abrasion data from Thompson *et al.* (2011) was incorporated into the analysis of total abrasion; this data for the bombardment of fresh bone by saltating sand grains was collected under the same experimental conditions utilised in the current study. However, the sediment size employed (sand with a median grain size of 200μm) is not tested directly herein.

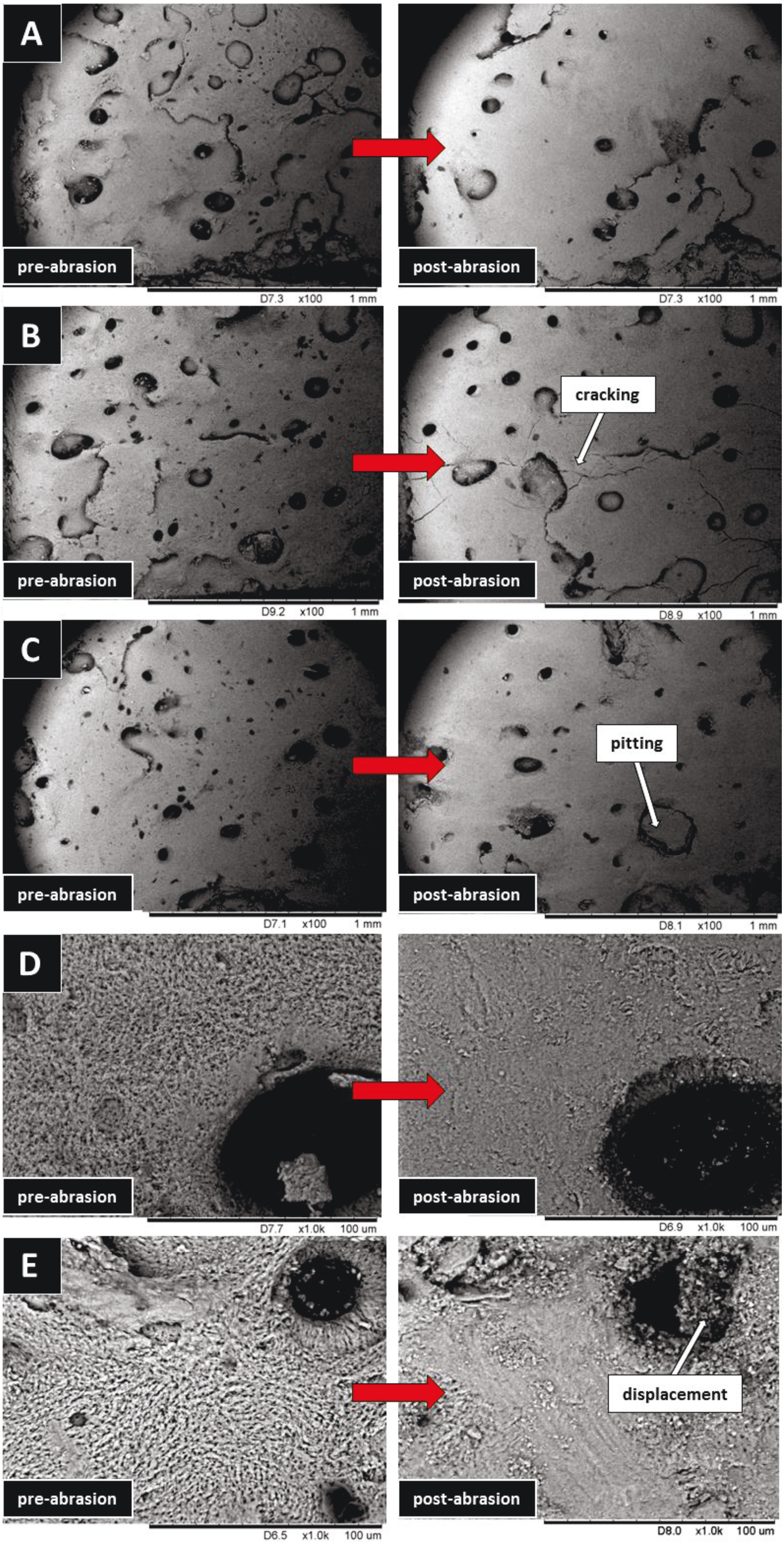


Figure 4. Examples of abrasion types:

A. Pre-abrasion surface (left) and post-abrasion surface (right) of bone after a period of bombardment imaged at x100 magnification (material missing from the bone's surface is an example of ablation abrasion).

B. Shows cracking at x100 magnification.

C. Shows pitting at x100 magnification.

D. Surface modified by smoothing ablation abrasion at x1000 magnification.

F. Shows displacement (movement of loose material across the surface, which often fills surface pores) at x1000

Therefore, this data is included in the results section so as to allow abrasion induced by 200μm sand to be directly compared with abrasion caused by the additional sediment sizes adopted in the current study.

3. Results

3.1. Abrasion types

For all sediment classes and sizes excluding silt (38μm) and fine sand (152.5μm) ablation is the dominant form of abrasion, accounting for an average of (76.3%) of total abrasion (**Figure 5**). The total percentage of ablation abrasion therefore follows highly comparable trends to those seen in total percentage abrasion (**Figure 6**). For the silt and fine sand sediment classes displacement shows the highest percentage occurrence (67.6%) (**Figure 5**), accounting for the reduction in abrasion shown by these size class.

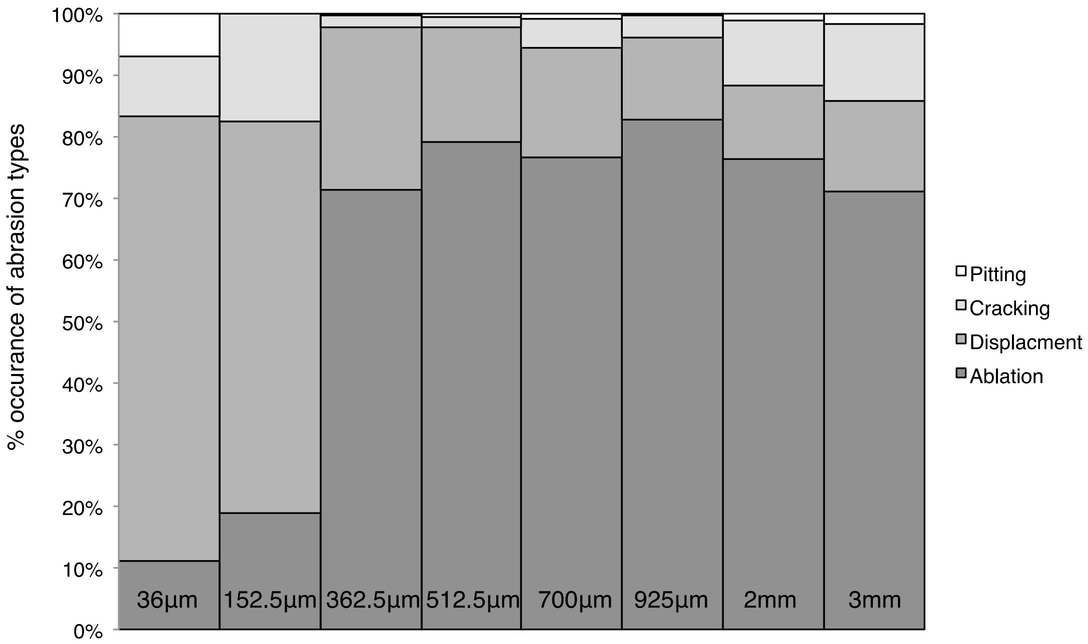


Figure 5. Percentage occurrence of abrasion types on bone surface for all sediments

3.2. Rate limiting variables

Abrasion rates show strong logarithmic trends, with abrasion propagation principally being a function of both increasing time and changes in sediment class and size (**Figure 6**). The degrees of abrasion are grouped according to sediment classification, with the largest gravel size inducing maximum abrasion after 120h, sand types showing intermediate abrasion, and silt producing minimal total abrasion. Abrasion rate data incorporated from Thompson *et al.,* (2011) follows these trends, showing consistency between studies. Two sediment sizes, 152.5μm and 362.5μm, do not follow clear logarithmic trends, displaying a reduction in abrasion during the last two-time intervals of 72 and 120 hours. As shown by Thompson *et al.,* (2011) the control bone displayed no modification, indicating that increased fluid shear force acting on the bone alone is not responsible for any observed changes.

Recorded variables of sediment grain morphology and their inherently related hydrodynamic properties (**Table 2**) were tested for significant influence on microabrasion rate using IBM SPPS 22 statistics software. A stepwise multi-linear regression model identified grain size ($p<0.001$), time ($p<0.001$), sphericity ($p=0.002$) and T value ($p=0.013$) respectively as the strongest predictor variables for abrasion rate (**Table 3**). Adjusted R squared values indicate these four controls account for 47.8% of the variance in the regression model.

Model A (all abrasion score data)

Adjusted R Squared	Standard error of estimate	Durbin Watson	Predictor Variables	Significance	Pearson Correlations	Beta	ANOVA
.478	5.478	1.527	Grain size	.000	.638	1.134	F= 50.770
			Time	.000	.278	.232	Sig = .000
			Sphericity	.002	-.589	-.500	
			T Value	.013	.625	-.949	

Model B (sand data only)

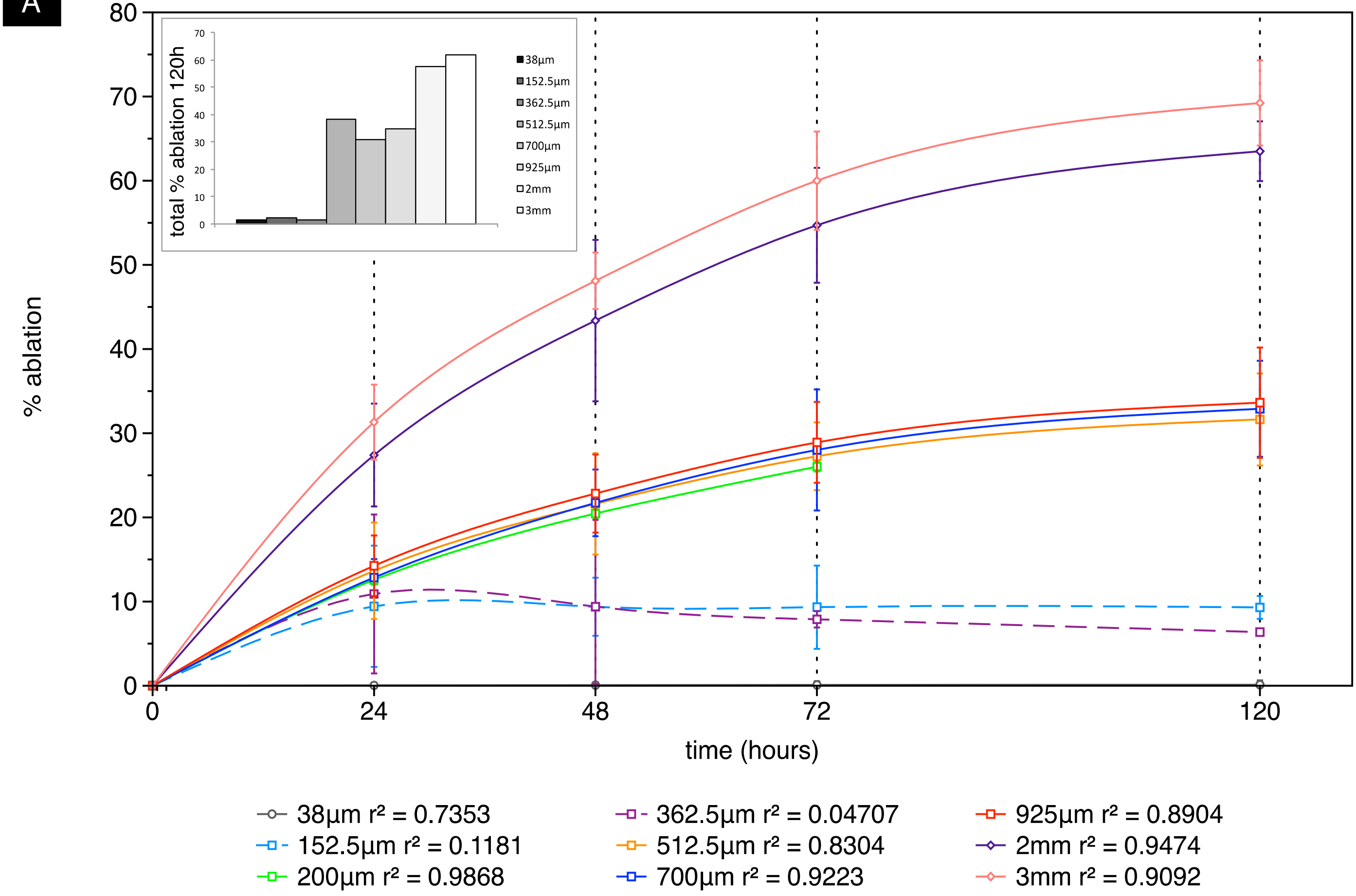
Adjusted R Squared	Standard error of estimate	Durbin Watson	Predictor Variables	Significance	Pearson Correlations	Beta	ANOVA
.082	5.0131	1.785	Impacts per second	.000	.297	.297	F=15.049 Sig= .000

Table 3. Stepwise multi-linear regression model summaries.

3.3. Abrasive potential within the sand sediment class

While there is a general trend of increased abrasion in relation to changing sediment size and class, the relationship between increasing grain size and abrasion propagation is more complex within the sand sediment class. Abrasion was highest for bone bombarded by the intermediate grain size of 512.5μm followed by 925μm, 700μm, 152.5μm and 362.5μm grains respectively (**Figure 6**). The reduction in abrasion shown by the 152.5μm and 362.5μm grains is explained by the frequent occurrence of scour pit formations around the bone, which resulted in a notable reduction in the number of impacts on the bones for the experimental duration (**Table**

A



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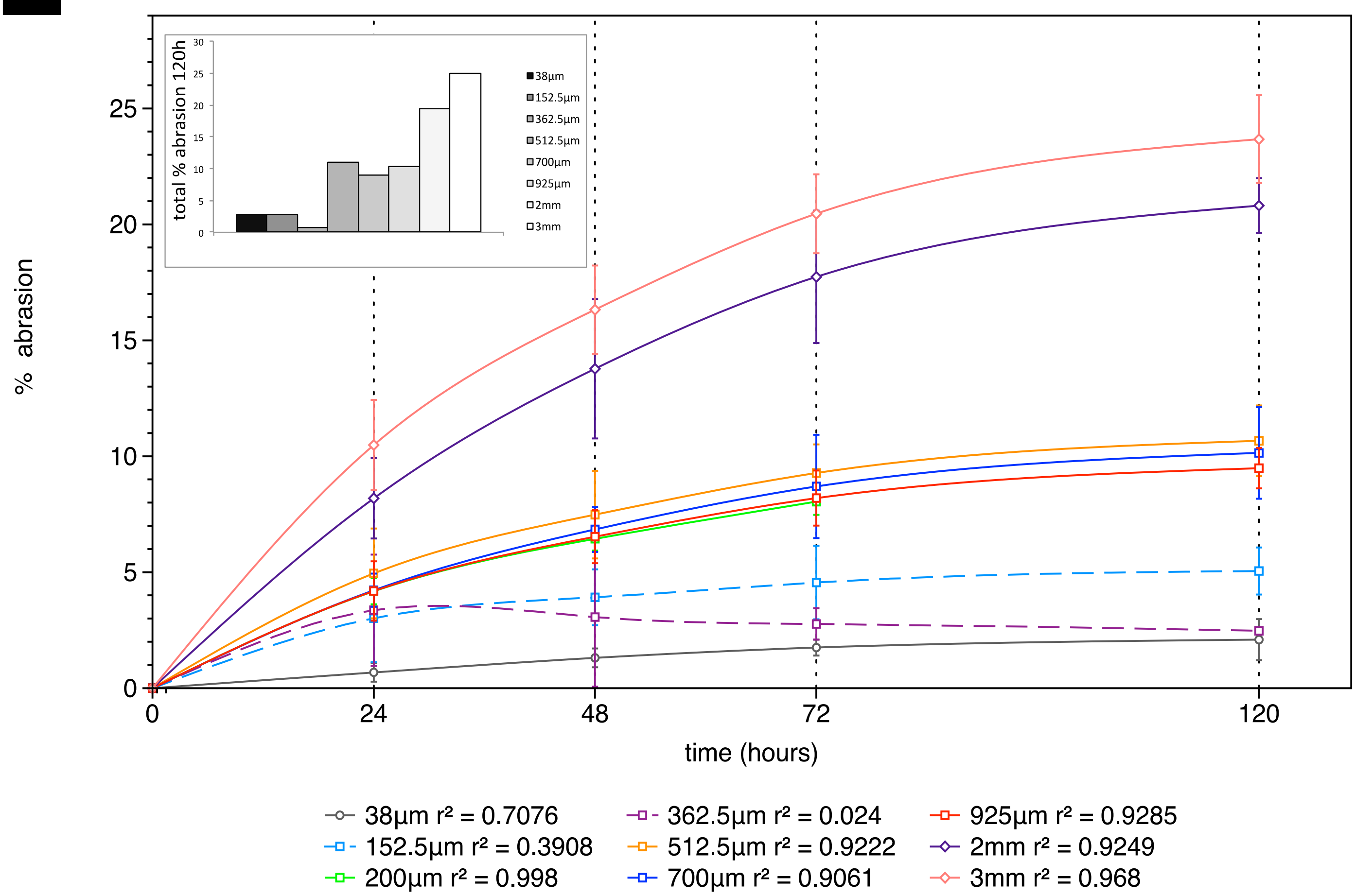


Figure 6. Trend lines and bar charts of **A.** total percentage of abrasion attributable to ablation between 0 and 120 hours. **B.** Total percentage abrasion between 0 and 120 hours. Note each data point represents average of abrasion scores from 270 cells. Discontinuous lines represent samples that experienced consistent scour pit formation on the upstream side of the bone.

2). Results confirm observations by Thompson *et al.,* (2011), who identified scour presence as having significant influence on microabrasion propagation rate.

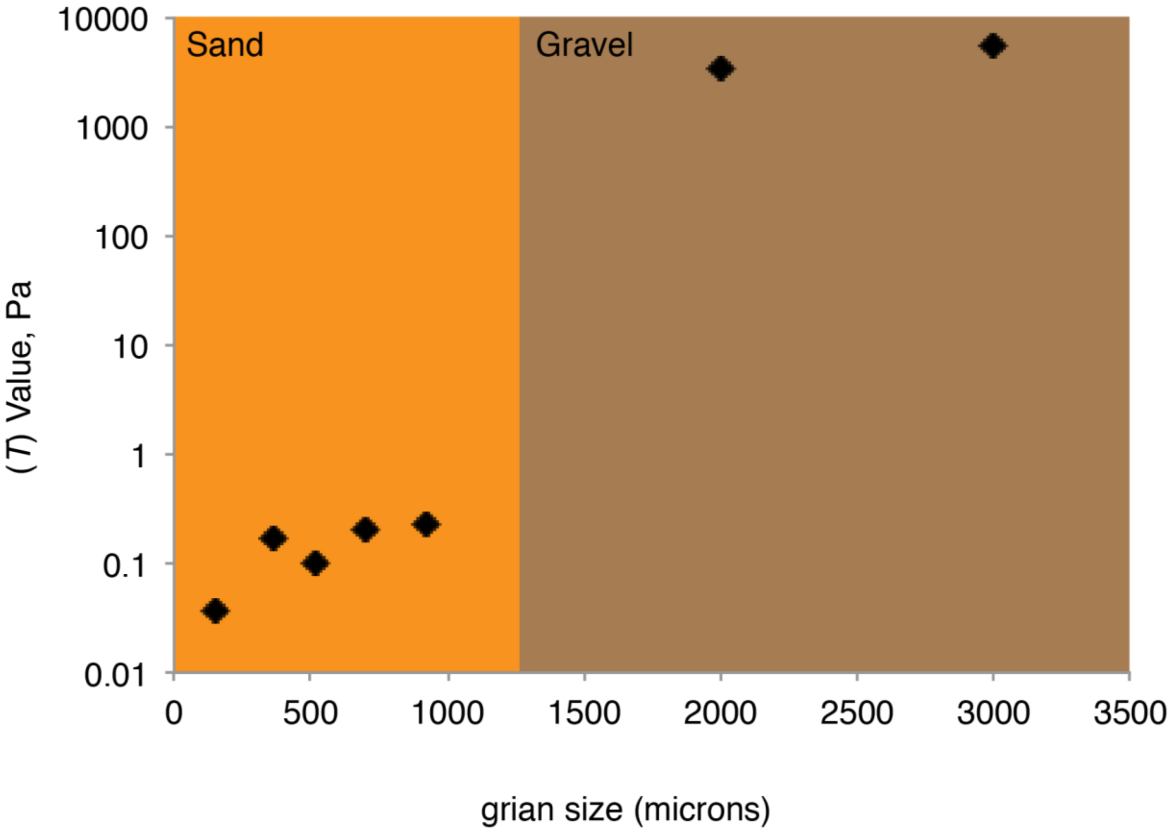
While the difference in final abrasion score for the remaining sand sizes is marginal, greater modification is also relatable to an increase in number of impacts per second. Bombardment by 512.5µm grains produced 21.8 impacts per second, 925µm produced 18.6 impacts, and 700µm produced 9.1, with the reduction in the latter again being due to intermittent scour formation on the upstream side of the bone. This trend was confirmed by additional regression analysis, which excluded abrasion data from the gravel class and the influences of time and *T* value, to assess which variables within the sand class had significant influence on abrasion. Analysis identified number of impacts as having significant influence ($p<0.001$) accounting for 8.2% of variance (**Table 3**).

It should be noted that sand types had far more numerous impacts than gravels (**Table 2**), however produced lower abrasion scores as a result of their grain morphology and smaller size, showing that when analysed across all sediment classes, grain size/morphology has more influence on abrasive potential than frequency of bombardment.

The observed trend of 512.5µm sand causing higher abrasion than other sand types can also be explained, in part, by the increased ability of an angular abrasive to penetrate the bone and remove material through deformation. The 512.5µm grains in this case were more angular (consisting of medium-high sphericity sub-rounded grains) while the 925µm, 700µm grains were rounded and highly spherical. Comparably, the 152.5µm grains used where more angular (consisting of medium-high sphericity sub-rounded grains) than the larger 362.5µm particles, which were highly spherical and rounded. These variations in grain morphology may translate into higher abrasive potentials, as relative to particle size the force applied by angular grains is more concentrated on the bone's surface than that applied by spherical particles. While regression analysis did not identify sphericity or angularity as having a significant influence on abrasion within the sand class it did have a significant influence on abrasion rate when data form gravel classes was included in the model (**Table 3**) and should therefore be considered of interest in future analysis

3.4. Ballistic momentum flux

Figure 7 indicates that *T* value increases with grain size, and that there is a strong logarithmic relationship between the force of the abrasive and the degree of abrasion bone experiences. Impact trajectory was consistent across all sediment sizes; averaging at 89.7 degrees to the plane of bone surface, due to the stationary bones creating uniform flow geometries. These consistent impacts at approximately 90 degrees confirm that maximum abrasion was being recoded. The statistically significant relationship ($p=0.013$) between force of the impacting abrasives and degree of abrasion, shows great potential for allowing observed modifications on bone to be related to the energy of the environment it may have passed through. Furthermore, calculated grain Reynolds numbers (Re) (see **Table 2.**) can be used to determine whether impacting grains were transported in steady or turbulent



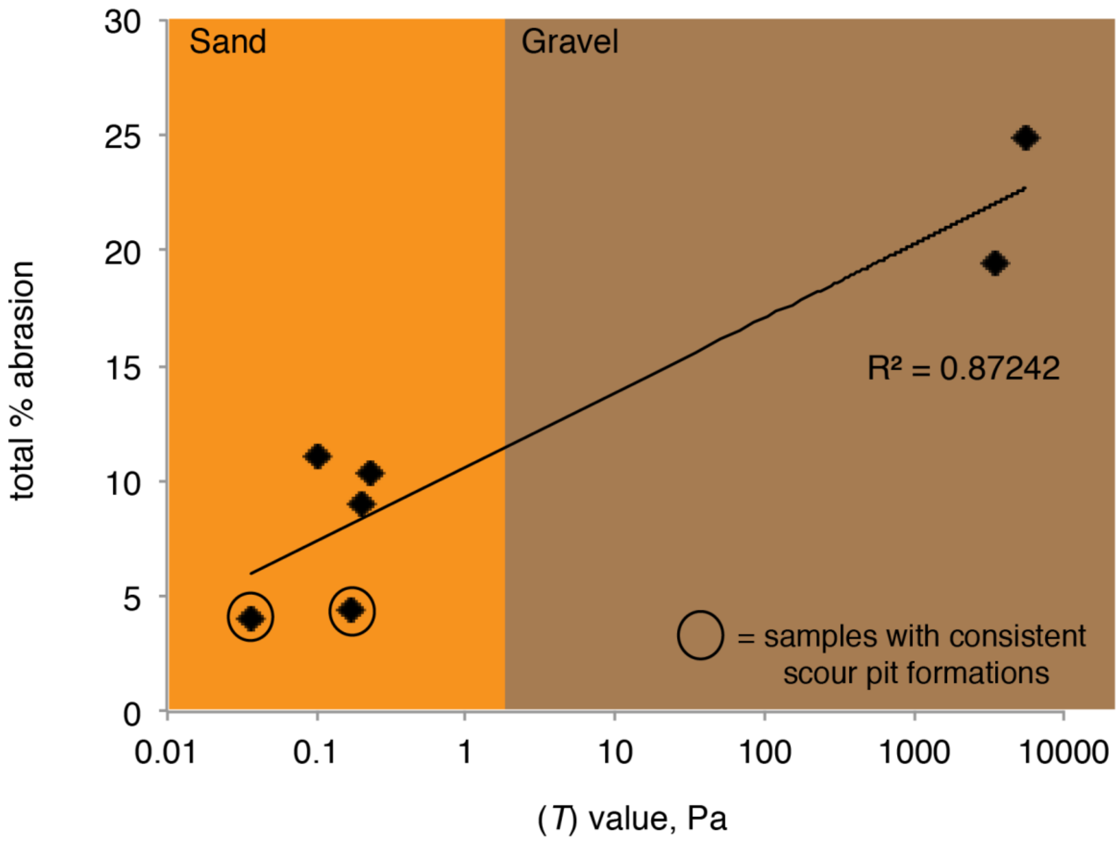


Figure 7. Top: Relationship between grain size and (T) Value. **Bottom:** Total % abrasion vs (*T*) value (Note total abrasion data points are averaged from 270 image cells).

conditions. Gravel grains in this study are shown to have Re values of >70, indicating turbulent flow conditions, whereas Re values for sand types range 5.40 - 54.09 (>5 <70) indicating laminar/steady flow conditions. This difference in the dynamic properties of the flow (the ratio of momentum forces to viscous forces), which is affiliated with increasing grain size, appears to have a direct effect on the abrasion propagation. While *T* value did increase with grain size, the fact that smaller grain sizes within the sand sediment class can display higher extents of abrasion is due to variations in number of impacts per second, and to the fact that the calculated *T* values do not adequately account for how changes in grain morphology affect the exact surface area of impacts. Therefore, more experimental work is needed to quantify changes in abrasive forces in relation to variable grain morphology; specifically changes in the surface roughness of the abrasive.

Our results suggest that within the sand sediment class there is a complex relationship between grain size, angularity/sphericity, number of impacts of the abrasive and the formation of scour, which is principally controlling abrasion rate. It is apparent that this relationship is as of yet imperfectly understood, and that the erosion rates of bone when bombarded by different sand sizes show very similar abrasion extents due to their closely related morphologies and hydrodynamic properties. While distinctions can be made concerning abrasive capabilities in relation to recorded variables, subtle changes in these measures may result in either larger or smaller grains inducing high levels of abrasion.

3.5. Differences in abrasion propagation

The basic proposition of this study, namely that different sediment types cause distinct variations in the way microabrasion progresses on bone's surface, seems well supported by the experimental results. Importantly, viewing abrasion at the two magnifications of x100 and x1000 allows for an improved understanding of differences in abrasion propagation.

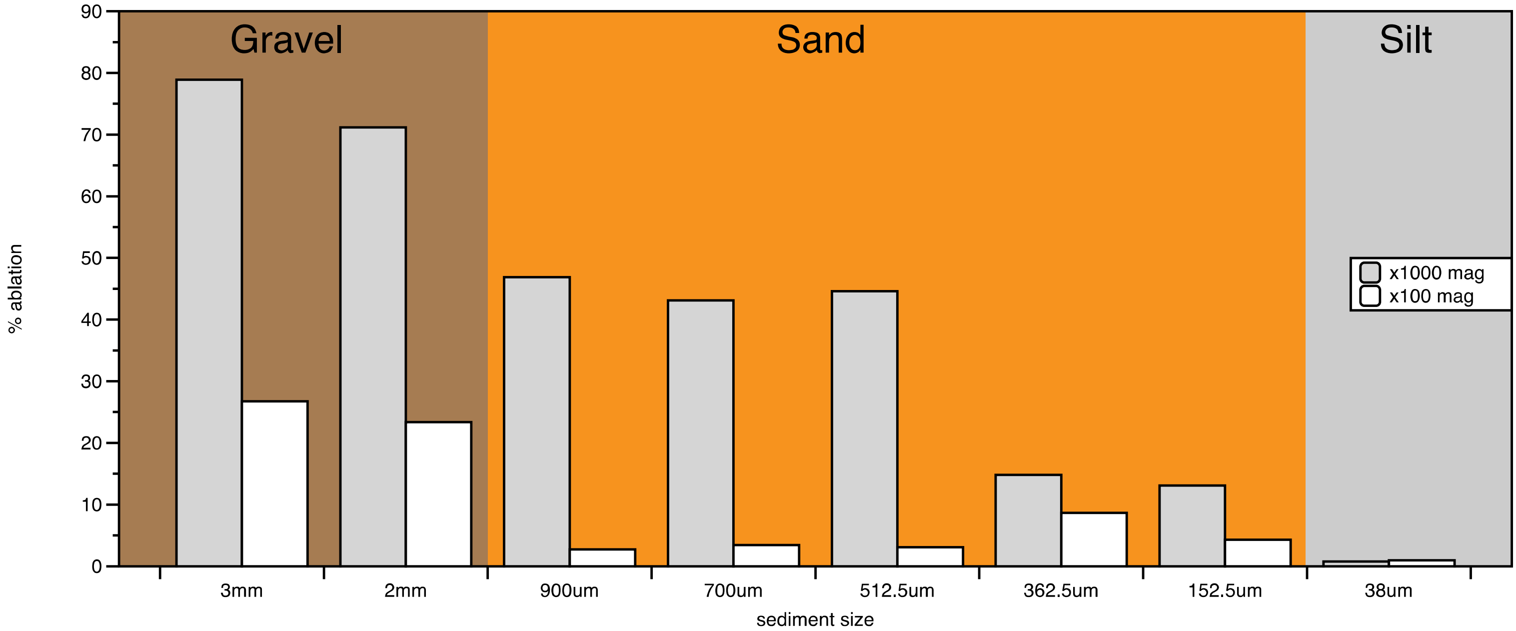


Figure 8. Percentage ablation recorded at both magnifications with sand showing minimal abrasion at x100 mag.

A large difference is apparent between the occurrence of ablation abrasion on bone bombarded by sands and gravel at x100 magnifications (**Figure 8**): Minimal abrasion is visible for sand classes, unlike gravels which cause high degrees of abrasion. However, sand induced abrasion is apparent when imaged at x1000 magnification.

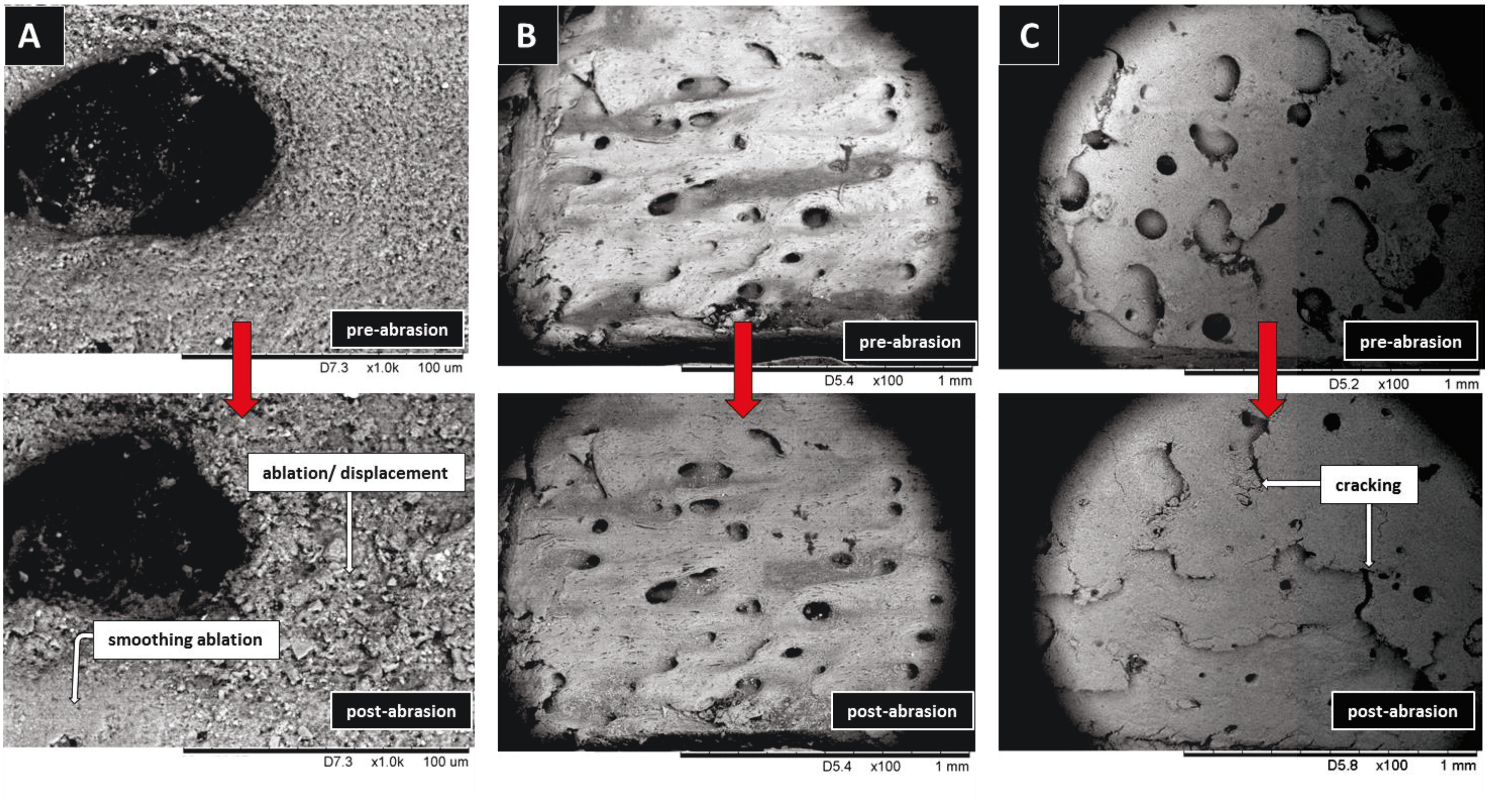


Figure 9. **A**. Bone surface abraded by sand at x1000 mag. **B**. Bone surface abraded by sand showing minimal abrasion at x100 mag (very little change is recordable). **C**. Bone surface abraded by gravel showing widespread cracking and ablation at x100 magnification

Image analysis also indicates that for gravel bombardment, abrasion proceeds through cyclical cracking. Initially loosely bound material is removed, then once a more compact surface is encountered large scale cracking proceeds to weaken the bone hence facilitating further volume removal; after which this process is repeated. It is apparent that sands do not have this capacity and instead cause widespread, but smaller scale volume removal, producing abrasion that is best described as smoothing of the bone surface (**Figure 9**).

Figure 10 demonstrates that there is a large rise in the amount of cracking caused by gravel-sized sediment over different time periods, while this remains consistent and low for sand classes. This difference in abrasion mechanism can again be explained by the larger size and more angular morphology of gravel grains facilitating more penetrative impacts. It is possible that the process of cracking is occurring for sand types but may simply not be apparent at the magnifications employed, or over the time periods involved. However, during the time intervals used in this study, imaging abrasion at x100 and x1000 magnifications allowed quantitative and qualitative distinction to be made concerning the sediment class that the bone was abraded by.

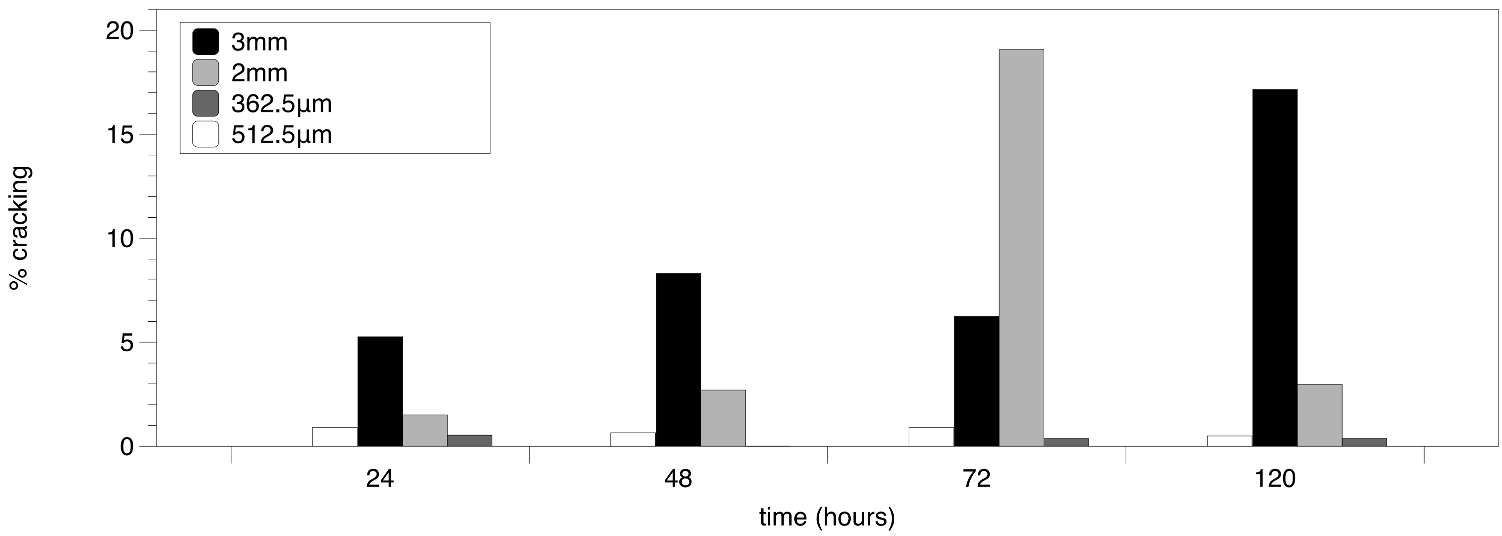


Figure 10. Cyclical cracking displayed by gravel types.

4. Discussion

4.1. Comparisons with previous abrasion experiments

The results presented herein are consistent with the findings of Thompson *et al.* (2011); with abrasion advancing rapidly during early periods of bombardment (24 and 48 hours), due to the removal of loosely bound surface material, after which abrasion rate decreased when more compact material was met. In addition, abrasion patterns produced by sand classes show homogeneity, with the majority of abrasion being recorded at x1000 magnification in both studies.

Our results also largely agree with other experimental water based abrasion studies. Cook (1995), utilising macroscopic techniques, found that abrasion increases when there is a change in the sediment class impacting bone, with gravel grains producing higher degrees of abrasion than sand. Similarly, Andrews (1995) notes that increased abrasion on water submerged bone is related to changes in sediment class, with the pebble class having the highest abrasive capabilities. Shipman and Rose (1983) observed microscopically that sand induced abrasion can cause smoothing of bone surface features. A later study by Shipman and Rose (1988) which employed SEM analysis indicates that within the sand sediment class, not only finer but more angular grains are capable of producing higher degrees of abrasion than larger and well-rounded particles.

Fernandez-Jalvo and Andrews (2003), using both macroscopic and microscopic observations, found that gravel particles cause the highest degrees of abrasion, and that finer particles from sand and silt classes display increased abrasive capabilities compared to coarser grains when bombarding fresh, fossil and weather bone, with the exception of silts and clays causing minimal changes to fresh material, a finding consistent with our own. However, it should be noted that a more recent study by Fernandez-Jalvo *et al.,* (2014) observed that coarser sand particles can, in contrast, induce slightly higher abrasion rates than finer particles. In addition, Fernandez-Jalvo et al., (2014) observed less cracking on bone surfaces abraded by gravel than recorded in our study; this difference may in part be due to the fragmented edges of fossil/weathered bone abrading more rapidly, hence smoothing out any features of cracking, and because tumbler barrel experiments may result in a higher rate of sediment-bone impacts than under flume based conditions, as they do not account for natural sediment transport modes and processes (Cook, 1995; Shipman and Rose, 1988). While Shipman and Rose (1983;1988), Fernandez-Jalvo and Andrews (2003) and Fernandez-Jalvo *et al.,* (2014) conducted tumbler based experiments, which produce less accurate representations of abrasion processes (Cook, 1995; Kuenen, 1956; Thompson *et al.,* 2011) overall their results are in good agreement with our own.

Bromage (1984) using SEM imaging observed that on the surface of forming lamellar bone, undergoing remodelling, deformation of superficial mineral clusters occurred during initial stages of bombardment. However, Bromage (1984) used fine salt particles in this study (ranging 5-150μm) which were projected onto bone surfaces using a Cavitron Prophy-Jet Dental Prophylaxis Unit, to observe the effects that different cleaning regimes and taphonomic processes have on the micromorphology of surface features. Therefore, it is questionable if this experimental abrasion process in sufficiently comparable to the processes of sediment abrasion in a natural aquatic environment. Microabrasion appeared to propagate more rapidly on these forming bone surfaces than on the bone surfaces used in our study. In addition, Bromage (1984) identified rough surface morphologies resulting from waterborne particle abrasion. While we did observe rough surface modifications, alterations more consistent with smoothing were present on bone abraded by fine particles. Bormage (1984) utilised archaeological material and fresh bone which was treated to remove organic components with a 7% solution of NaOCl. Therefore, it is likely that these observed differences are due to the more fragile bone surfaces used in Bromage's (1984) study being worn more readily during initial stages of bombardment.

4.2 Advantages of microscopic analysis

While there is a general agreement between macroscopic and microscopic observations of abrasion, the latter has a number of distinct analytical advantages. Firstly, macroscopic analysis of smoothing or rounding is more susceptible to the issue of equifinality, where abrasion by different sediment classes may produce very similar abrasion features on bone's surface (Cook, 1995). Recording multiple markers of abrasion visible through microscopic imaging, helps to overcome the subjective nature of macroscopic observations and allows for more accurate distinctions to be made concerning the class of sediment which bone has been abraded by. This understanding of variances in abrasion propagation between sediment classes may be particularly helpfully for determining the transport pathways of remains by elucidating the different sedimentary environments a bone may have passed through.

Furthermore, smoothing and rounding are not direct measures of material removal. Consequently, macroscopic analysis of abrasion can only place abrasion into broad categories of change; microscopic analysis helps to overcome this by facilitating a more sequential understanding of abrasion propagation. Therefore, temporality of bombardment can be established more accurately than through gross morphological assessment. Furthermore, taking multiple images of bone's surface allows for more confidence in observed abrasion trends through averaging and statistical analysis.

Importantly, DeBattista *et al.* (2013) show that different diagenetic and pathological changes to bone's surface, at the micro-level, are morphologically distinct from those caused by sediment abrasion; demonstrating the applicability of this analysis to a wide range of bone states and types.

A disadvantage to microscopic imaging is that after a certain period of abrasion (which is yet to be defined) the entirety of bone's initial surface features will be removed; meaning further analytical techniques may be needed to analyse longer periods of abrasion. However, overall, microscopic analysis is better suited to assessing the complexities of abrasion propagation than more qualitative measures that afford less detail. We employed SEM analysis in this study as this instrumentation is known to produce images with good depth of field, hence facilitating the capture of small abrasive modification. However, low powered optical and stereo microscopes can also image bone surfaces at the magnification employed herein and would therefore be a suitable alternative to SEM imaging.

4.3. Time resolution

It should be noted that degrees of abrasion observed in this study are not representative of those that would be found on transported bone. Timescales presented herein represent idealised conditions of maximum abrasion, and are not likely to occur consistently in the field. Chu *et al.,* show in their 2013 study of microabrasion propagation on mobile and stationary flint artefacts, that active artefact transport results in a reduction in abrasion rate. This is most probably due to the smaller number of impacts the material will experience in transit and a reduction in force and concentration of these impacts over a specific surface area due to the abrasives and the impact surface being in motion simultaneous. Therefore, we predict that under the same hydrological conditions it would take significantly longer periods of times for the degrees of abrasion recorded on stationary bone in this study to propagate on bone in motion. Our controlled experiments therefore represent longer timescales in the field, which are yet to be defined through actualistic experimentation in natural systems.

How flume-based abrasion relates to real-world abrasion rates can be approximated. For example, Pattiaratchi and Collins (1984) show the predicted transport rate of current driven sand (d50=404μm) in the Bristol Channel, as being between $5x10^{-3}$ and $93x10^{-3}$ g/cm/s. Taking the largest predicted transport rate ($93x10^{-3}$ g/cm/s) and assuming that c.15% of bedload is in saltation (Middleton and Southard 1984), this translates to a maximum sediment impact mass of 6kg/cm over 120 hours in a natural setting. The lowest predicted transport rate ($5x10^{-3}$ g/cm/s) translates to a minimum sediment impact mass of 0.324kg/cm in 120 hours. Our flume-based observations of 512.5μm sand show the mass of sediment impacts to be 15.17kg/cm in 120 hours. Therefore, our flume-based abrasion rates for 512.5μm sand represent a range of between 300 - 5619 hours (a maximum of c.8 months) of abrasion in natural settings, depending on the hydrodynamic conditions at the time of submersion.

4.4. Case studies

As stated in **Section 4.3.** actualistic experimentation is needed to accurately relate experimental microabrasion ates presented in this study to bombardment times in natural settings. However, the data presented herein currently have good potential applications in helping to determine the different sedimentary environments bone has been exposed to. To test the utility of our experimental findings three animal bone samples recovered from coastal aquatic contexts were imaged and the microabrasion analysed. Abrasion data was linked to hydrological and marine seabed sediment data to demonstrate how recorded microabrasion can reflect the different sedimentary contexts bone has passed through, hence helping to establish the transport histories of the remains with more confidence. Lastly, a single published SEM image of the surface of a fragmented fossil bone, recovered from a drowned terrestrial site, was analysed. In addition to there being good agreement between abrasion data recorded in a previous set of experiments conducted by Thompson *et al.,* (2011) using the same methodology (see **Section 3.2.**) these case studies demonstrate how our results can be applied to material outside the lab based taphonomic models present herein.

4.4.1. West Angle Bay, Pembrokeshire, UK

The proximal end of a sheep femur bone was recovered from West Angle Bay, Pembrokeshire. The sample displayed a total percentage abrasion score of 25.5%. When compared to our experimental studies this abrasion extent suggests extensive bombardment by gravels (>120 hours flume based abrasion). Wide spread cracking was recorded at both x100 and x1000 magnification (**Figure 11**), signifying abrasion by gravel types. In addition, total percentage ablation recorded at x1000 magnification was very high (98.3%), with the bone surfaces showing extensive smoothing of mineralised collagen fibrils indicative of abrasion by sands. The dominant hydrological and sedimentary processes at this sandy beach are characterised by high energy wave action (>1200 N/m2) and moderate current energy (130-1160 N/m2) at the seabed (Data.gov, 2016). The beach is supplied by offshore marine Holocene sediments consisting of gravelly sand (c.0-10km from site). Further offshore there are areas of marine Holocene sediments; mainly gravel and sandy gravel to the northwest, and sand and slightly gravely sand to the southwest (c.>10km from site) (MareMap, 2016). Wave action within the areas surrounding the littoral sub cell is known to produce strong on and offshore movement of sediments (Motyka and Brampton, 1993)

The occurrence of different abrasion types across the bones surface reflects the local and regional seabed sediment well. In light of the abrasion data, the known sedimentary and hydrological context, as well as the gross morphological state of the bone (recovery of the proximal femur only) it can be suggested that the bone was transported from the north of the site and most probably underwent a period of abrasion by offshore gravels before being abraded by nearshore sands prior to deposition. The recorded abrasion indicates that it is unlikely that the bone was transported from the southwest of the site where sands are the dominant bedload sediment type.

4.4.2. Lepe beach, Hampshire, UK

A sheep metacarpal bone was recovered from Lepe beach, Hampshire. Cracking was widely distributed across the bone's surface at both magnifications (**Figure 11**) indicating abrasion by gravels, with the bone displaying a total percentage ablation score of 20.7% reflecting extensive abrasion by gravel, equivalent to c.120hours of flume based abrasion. Recorded percentage cracking was higher at x100 magnification that at x1000; this greater extent of cracking at the lower magnification is indicative of a period where the bone surface is weakened but wide scale material removal, visible at x100 magnifications, has not yet occurred. The bone also displayed high ablation wear at x1000 magnification (98.3%) caused by smoothing of the surface through sand induced abrasion. At this site the dominant hydrological and sedimentary processes are characterised by low energy wave action (0-130 N/m2) at the sea bed, with high current energy (>1200 N/m2) to the sites west and moderate current energy (130-1160 N/m2) to the east, at the mouth of the Solent estuary (Data.gov, 2016). Seabed sediment is complex in the surrounding area; predominantly coarse marine Holocene sediments consisting of sandy gravel and gravel are located to the west of the site (c.0-10km), with Holocene muddy and coarse sand to the east (c.0-10km) (MareMap, 2016). The beach sediment consist chiefly of coarse sub-angular flint gravels, and pebbles, transported by littoral drift from southwest of the site, however directly offshore there are areas of sand and muddy sand (MareMap, 2016).

Again recorded microabrasion reflects the surrounding sedimentary context well. As we used fine gravels in our flume experiments it is reasonable to suggest that bombardment by the coarse grains present in the Solent would result in an increased abrasion rate (meaning the recorded abrasion is most probably equivalent to <120hours of flume based bombardment). In light of this data we can suggest that the recorded microabrasion represents bombardment by coarse gravels in a high energy setting. Therefore, rather than being transported through the predominately sandy eastern Solent, it is probable that the sample was moved from the southwest of the site in conjunction with the predominate direction of littoral drift in the area and was further abraded by sand close to the shore before deposition.

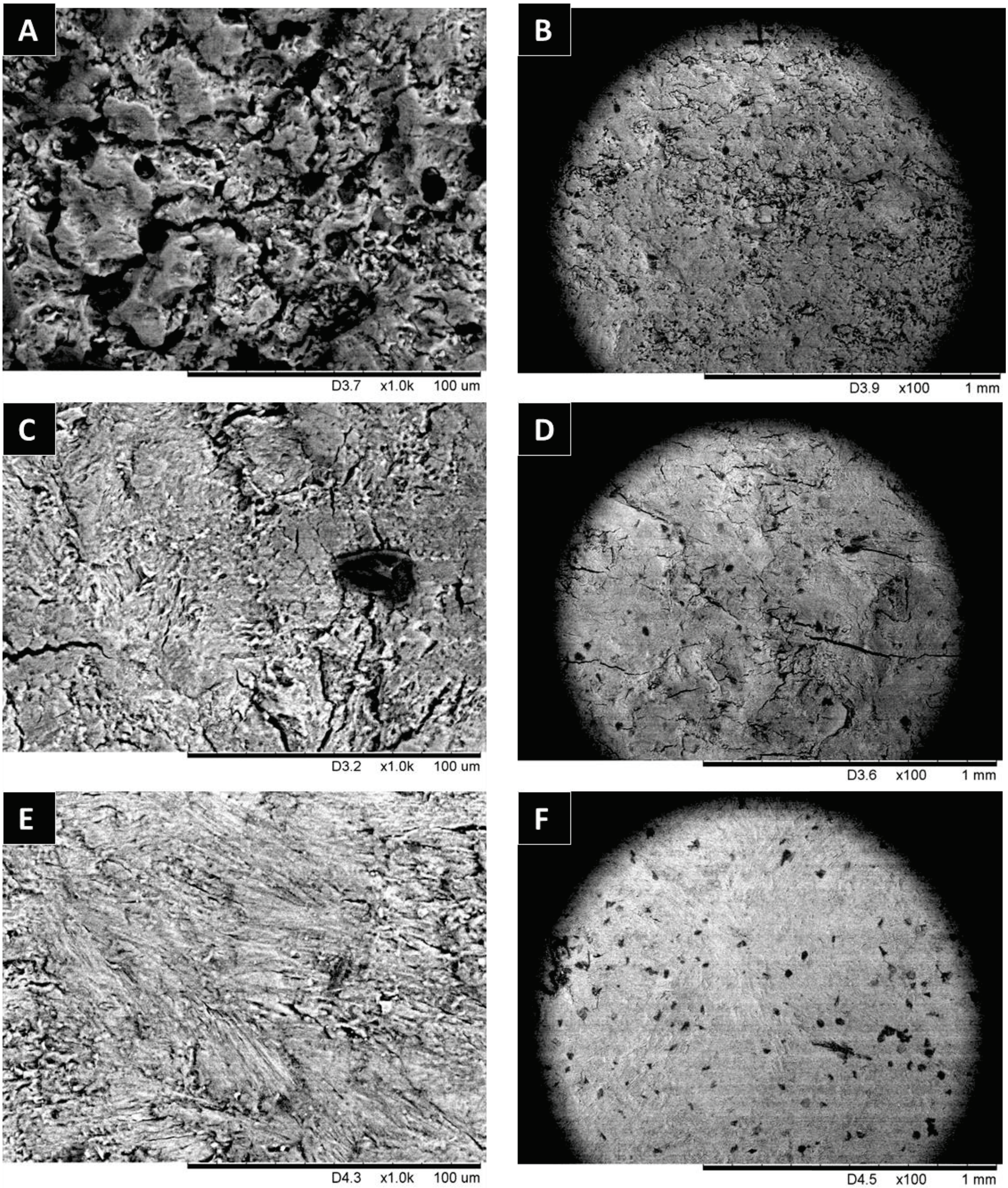


Figure 11. A. Cracking on proximal sheep femur imaged at x1000 magnification and **B.** x100 magnification. **C.** Cracking on sheep metatarsal imaged and x1000 magnification and **D**. x100 magnification. **E.** Bird bone surface, showing ablation in the form of smoothing at x1000 magnification **F.** Minimal abrasion recorded on the surface of the bird bone at x100 magnification

4.4.3. Gyllyngvase Beach, Cornwall, UK

A bird tibiotarsus bone was recovered from Gyllyngvase Beach, Cornwall. The sample displayed minimal ablation (3.70%) at x100 magnification, but showed notable ablation wear of (83.53%) at x1000 magnification (**Figure 11**), reflecting abrasion predominantly by sand classes. A total percentage abrasion score of 12.8% was recorded (equivalent to slightly over 120hours of flume based bombardment by coarse sands). The beach is characterised by low energy currents at the seabed (0-130 N/m2) and moderate wave energy (130-1160 N/m2) (Data.gov, 2016). The surrounding seabed sediment load consists of coarse, slightly gravelly sand (c.0-10km from site) (MareMap, 2016). There are deposits of Holocene sands to the west of the site, and sand and Pre Quaternary rock to the east (c.>10km from site) (MareMap, 2016). Sediment transport in the areas littoral sub cell generally consists of nearshore circulation of sands, with very little influence from littoral drift (Motyka and Brampton, 1993)

This abrasion data, in particular the limited abrasion recorded at x100 magnification, indicates that transport over the Pre Quaternary rock to the east did not occur. Therefore it is less likely that the sample was transported from east of site; rather the abrasion data suggests the sample entered the water from the west of the site, or at the site itself, and was modified by near shore sand abrasion only.

4.4.4. Inundated Late Pleistocene terrestrial site, continental West Coast of South America

A single SEM image published in Cartajena *et al.,* (2013) (Figure 6A, pp 53) showing the surface of a fragmented palaeolama humerus bone, recovered from an inundated Late Pleistocene terrestrial assemblage on the continental West Coast of South America, was analysed. Only one image was available of the bone's surface which was comparable to a magnification we employ in our study (x1000 magnification), meaning calculations of abrasion at two different scales was not possible, and abrasion scores could not be averaged from multiple images. A total percentage abrasion score of 13.89% was calculated for the sample, with 85.33% of recorded abrasion being caused by ablation, 8% by cracking, and 6.67% by displacement. Cartajena *et al.,* (2013) indicate that at a gross morphological level abrasion attributable to the action of marine sands was a commonly observed taphonomic alteration to bones from this site; with polishing and smoothing being homogeneous, affecting 99% of the bones' surfaces. As the majority of the abrasion is attributable to ablation, and minimal cracking was recorded, the microabrasion data supports the gross morphological assessments made by Cartajena *et al.,* (2013) and the conclusion that deformation of the bone's surface was caused by *in situ* sand action. In contrast to our experimental samples there appears to be greater depth of abrasion on the fossil bone (a modification also observed by Thompson *et al.,* (2011) on fossil remains), however this difference is not easily assessed using 2D images. It is likely that this disparity is related to the brittle surface of fossil bone being removed more easily than that of the fresh bone samples employed in our study. It should be noted that some surface material loss from the fossil bone may be attributable to periods of aerial weathering at the site prior to inundation (Cartajena *et al.,* 2013, pp

51). Despite this fact, the recorded abrasion does reflect the surrounding marine sedimentary context well; again demonstrating the utility of microabrasion for making assessments concerning the different sedimentary environments bone has been exposed to.

4.4.5. Potential applications in the archaeological record

An improved understanding of taphonomic signatures of abrasion on bone has a number of advantages when interpreting water transported remains from the archaeological record. Firstly, the presence of micro-abrasion on bone can indicate whether remains have been moved from a primary depositional context, while also helping to establish whether the cause of this displacement is due to natural taphonomic events rather than anthropogenic influences. Being able to correctly establish that an assemblage has been biased by taphonomic processes has important implications for contextual interpretation of skeletal deposits, the definition of their spatial and temporal significance, and subsequently their cultural conations and demographic or ecological affiliations.

Furthermore, if skeletal deposits are recognised as allochthonous in nature, then diagnostic signatures of abrasion may help to the elucidate transport pathways of remains, hence facilitating interpretations of the material's potential primary depositional environments. As the above case studies demonstrate, empirical data can be implemented to better establish the different sedimentary environments bone has been exposed to; hence allowing the most probable direction of transport to be established in relation to know sediment distribution data. In addition, if rates of abrasion propagation are better understood in natural setting this may also allow durations of transport to be better determined. Such information used in conjunction with isotopic data, hydrodynamic sorting data (the relative abundance of different skeletal elements and taxa) and other pertinent taphonomic information may help to elucidate the provinces of the remains, hence allowing disassociated material to be reassigned the contextual relevance on which many subsequent archaeological interpretations are based.

4.5. Issues concerning the application of taphonomic models in the field

This preliminary study indicates that a quantitative approach to understanding and analysing microabrasion on bone has promise and merits further investigation. However, predictable abrasion rates may be influenced by the potential complexity of taphonomic pathways in natural aquatic systems and variations in the morphological and physiochemical properties of bone, and therefore need to be further assessed.

A major issue to overcome when accounting for variability in natural environments are influences which affect linear abrasion propagation, hence causing discrepancies between measures of abrasion and periods of submersion. Periodic burial in bottom sediment and the formation of bed features, such as scour, around bone will reduce the amount of abrasion bone experiences over fixed time intervals (DeBattista *et al.,* 2013; Thompson *et al.*, 2011), as will periods of flotation (Evans, 2014). Additionally, initial modifications to bone may be obscured or altered by subsequent processes (Cook, 1995). For example, bone may pass through multiple sedimentary contexts, causing the abrasion by one sediment class to disguise alteration by another. Therefore, additional studies should assess the reliability of laboratory-based observation in natural settings, by adopting an actualistic experimental approach. This approach should record and incorporate hydrological and sedimentary data, and track bone transport in detail, hence allowing observed abrasion to be related to real world submersion times and transport pathways.

Differences in abrasion propagation between fresh, weathered, archaeological and fossil classes of bone have been investigated in past studies (Cook, 1995; Fernandez-Jalvo and Andrews 2003; Thompson *et al.,* 2011); as a general rule, abrasion progresses more rapidly in fossil and archaeological material than in fresh bone, as higher levels of collagen degradation in the former result in increased brittleness. The way in which variation in bone's structural integrity within distinct weathering classes may affect microabrasion rate has yet to be tested, and may be particularly important to determine for archaeological material due to the wide range of diagenetic states this bone class demonstrates. To address this issue we suggest that future studies assess variations in microabrasion rate in conjunction with more quantitative measures of bone tissue quality, such as bone mineral density, crystallinity index; mineral to matrix ratio; and total collage content. In addition, observed abrasion rates of fresh bone in this study need to be compared to archaeological material to fully assess any differences in microabrasion propagation rate.

5. Conclusion

This study provides preliminary data concerning quantitative analysis of microabrasion propagation on bones' surfaces, caused by mobile sediment abrasion. SEM imaging has shown that different sediment classes (silt, sands and gravels) produce distinct levels of abrasion on bone at a microstructural level. Clear differences between the mechanisms that result in different abrasion types and extents have been identified; it being shown that a reduction in sphericity and increase in size of gravel grains causes abrasion to advance through cyclical cracking, whereas abrasion through smoothing of bone's surface occurs more frequently for sand and silt classes. Such observations demonstrate potential for allowing distinctions to be made concerning the different sedimentary environments bone may have passed through.

A Stepwise multi-linear regression model identified changes in sediment size, duration of exposure to abrasion, grain sphericity and abrasive force as the strongest rate limiting factors controlling microabrasion propagation. These results indicate that observed modifications to bone are highly relatable to the energy of the aquatic environment it may have passed through.

Microscopic analysis has been shown to have a number of distinct advantages over gross morphological assessments of abrasion. Most notably the higher degree of resolution microscopic analysis provides facilitates a more sequential and detailed understanding of abrasion propagation; hence allowing periods of bombardment to be determined with a higher degree of temporal resolution than is possible through macroscopic observations.

A series of case studies has shown initial successes in relating recorded microabrasion to the different sedimentary contexts bone was exposed to; hence demonstrating the utility of this methodology for analysing remains recovered from natural settings.

In conclusion, the analysis of microabrasion propagation on bone retrieved from water has potential to be used in conjunction with other methodologies to allow remains' submersion times and transport pathways to be established with a higher degree of resolution than is currently possible through gross morphological assessment. However, it is clear that further research is needed to determine whether laboratory-based models of abrasion are appropriate analogues for diagentically altered bone recovered from water in natural settings.

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